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Linkage analysis for water-carbon nexus in China

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HIGHLIGHTS

- The linkage analysis is used to investigate the water-carbon nexus in China.
- Important regions as water-carbon nexus nodes are identified.
- Outsourcing of resources and emission for stringent environmental target is suggested.

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ABSTRACT

The shortage of water resources and threat of climate change are two major global problems associated with economic development. One vital issue is to coordinate water resource utilization and CO_2 mitigation considering their coupling mechanism in socio-economic systems. This study employed linkage analysis based on a multi-regional input-output database to identify the roles of economic sector and pathway with respect to water resource utilization and CO_2 emissions, and to characterize each sector along the entire supply chain. A case study was conducted to address the status of coupled water and CO_2 in China. The results showed that Hebei, Shandong, and Inner Mongolia provinces are the major water-carbon nexus nodes for net forward linkage (net exports), i.e., mainly exporting products, embodied with large amounts of scarce water and CO_2 emissions, to fulfill the demands of other economic sectors. Guangdong, Zhejiang, Shandong, Jiangsu, and Shanghai were found to be the major water-carbon nexus for net backward linkage (net imports), i.e., mainly importing products, embodied with large amounts of scarce water and CO_2 emissions, from other sectors to meet their requirements. It can be concluded that exporter nodes are under severe water stress and have stringent CO_2 emission reduction targets, while importer nodes might transfer water stress and CO_2 emissions to the other regions via the supply chain.

1. Introduction

Water and CO_2 associated with anthropogenic production activities are intertwined within the socio-economic network, and the spillover effects between different regions make the water-carbon nexus a complex issue [1–4]. These two elements are considered coupled instead of independently because a single target policy for water or CO_2 might intrinsically influence the other via the supply chain and regional trading activities [5–7]. In addition to the nexus between water resources and CO_2 emissions, the characteristics of water stress and CO_2 reduction targets in different regions should also be considered [8]. For example, regions with serious water stress conditions and stringent CO_2 emission reduction requirements might spill over into other regions with moderate water stress conditions and lower environmental standards [9,10]. Therefore, nationally, the water-carbon nexus should be shaped with consideration of the linkages over the supply chain and the spillover effects among different regions for rational policy formulation.

The water-carbon nexus has been evaluated on specific production levels, e.g., in terms of the electricity production process and the water production process, via the methods of life cycle analysis (LCA), hybrid LCA, and material flow analysis [1,3,7,11–13]. Venkatesh et al. [1] used LCA to quantify product inflows and outflows when investigating the water-energy-carbon nexus in the water supply and sanitation systems of four cities. Stokes et al. [2] evaluated the economic benefits of the technology for the reduction of greenhouse gas emissions in terms of the potential conservation of water and energy resources via a bottom-up approach, i.e., process-based and economic input-output (IO) analysis-based LCA. Dodder et al. [3] investigated the effects of low-carbon electricity generation operations on water withdrawals or consumption with consideration of the water-carbon trade-offs throughout all life cycle stages. Li et al. [5] adopted hybrid IO-based LCA to analyze CO_2 emissions and water consumption related to wind power generation in China. They showed that wind power generation could reap double benefits, i.e., CO_2 emission reductions and water

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conservation when increasing the share of wind power. Zhang et al. [7] established two multiple linear regression models to measure the additional energy consumption and water-saving effects of a coal powered generation plant with air-cooling equipment compared to one with a wet cooling system. Laurenzi et al. [11] conducted LCA to evaluate the freshwater consumption and greenhouse gas emissions correlated with Bakken tight oil. Xin et al. [13] also used hybrid LCA to assess the impacts of electricity production on water quantity and quality as well as on CO_2 emissions. This bottom-up approach is suitable for reflecting the balance between water consumption and CO_2 emissions for a specific production activity; however, at the regional level, it would be inadequate for evaluating the linkages and spillover effects between regions with respect to the water-carbon nexus [4,14,15]. Although there have been some advances regarding the water-carbon nexus in terms of intermediate production processes, further exploration on the national level is required, especially regarding the interaction between paired regions [14,16].

Top-down approaches can explore the interactions among different regions from a more comprehensive perspective than bottom-up approaches because they track flows through both direct and indirect pathways, reflecting the influence of final demand driving on the water-carbon nexus [5,17,18]. Multi-regional input-output (MRIO) analysis is a typical top-down method used for the evaluation of resources or of the transfer of pollution within an economic transaction network [19,20]. It can demonstrate not only the dependence of different regions but also the pressure on resources or pollution transfer from both production and consumption perspectives, which facilitates explanation of the connection between paired regions with respect to certain environmental factors [21,22]. MRIO, extended with environmental coefficients, has been used widely for evaluations of water consumption, energy utilization, and CO_2 emissions on regional, national, and global levels [18,20,21,23–25]. Linkage analysis, derived from IO analysis, is able to assess the position of a certain sector or region within an economic system with regard to the total imports or exports during the entire production process [26,27]. It mainly includes forward linkages (exports) and backward linkages (imports) in the explanation of the role of a certain sector or region within the larger picture of an economic system, and it reflects the direction and effects of resource or pollution outsourcing from affluent regions [4,28].

China is facing a serious condition of imbalanced water resource distribution, and the North Water Transfer Project has been implemented for the redistribution of water resources in an attempt to alleviate water scarcity in Northern China [23]. In relation to CO_2 emissions, China contracted in the Paris Agreement to the obligation to lower its carbon intensity by 60–65% compared with the 2005 level and to reach peak CO_2 emissions by 2030 [29]. Thus, China has enacted detailed CO_2 reduction targets for different regions with consideration of their economic development conditions and reduction pressures [30], and it has established a carbon market in developed areas [31]. Therefore, to avoid unintended effects on other environmental indicators and to realize co-benefits and the balance of these two vital factors, integrated understanding of the water-carbon nexus among the regions of China is essential for developing structured policies related to water and carbon issues.

Most recent studies have evaluated the influences of economic trade activities in terms of virtual water, energy, and carbon embodied in intermediate products and final consumption. However, few studies have considered the responsibility for the water-carbon nexus transferred to the wider economy once products are exported from one region to its trading partners, i.e., the water-carbon nexus balance between the imports and exports of a region and its trading partners is ignored. To address this important research gap, this study used linkage analysis to explore the water-carbon nexus in terms of the imports, exports, and final demands of each region, i.e., the responsibilities for water consumption and CO_2 emissions from both production and consumption perspectives were decomposed. Regional disparities of water stress and carbon reduction pressure were also examined to illustrate the inequalities among and within the various regions of China.

The remainder of this paper is arranged as follows. Section 2 presents the methods adopted and a case description, i.e., the combination of MRIO with linkage analysis and basic environmental information of China's 30 regions. Section 3 illustrates the results of the investigation of the water-carbon nexus in China's 30 regions, such as the calculations of net forward linkage and net backward linkage in terms of the water-carbon nexus. Sections 4 and 5 present discussions and conclusions, respectively, based on a range of modeled results.

2. Methods and data

2.1. MRIO

The MRIO approach is to model environmental impacts with consideration both of the entire supply chain and of the pollution and resource consumption at each production stage [32], which can illustrate the interrelationships of various sectors within an economy and reveal the outsourcing effects of interregional trade [9,10]. The Leontief inverse matrix can depict the direct and indirect consumption flows driven by the total final demand, and analyze the spillover effects on resource or pollution transfer from affluent regions to less developed areas via tracking the emission/resource distribution through supply chains [23].

The basic MRIO model can be described as:

$$X = Z + Y, \tag{1}$$

where X is the total input or output, Z is the intermediate flow, and Y is the final demand. A^{rs} is defined as the technical coefficient submatrix:

$$A^{rs} = (a_{ij}^{rs}) = \left(\frac{z_{ij}^{rs}}{x_j^s}\right) \tag{2}$$

where z_{ij}^{rs} is the cross-sectoral monetary flow (i and j represent sectors, and r and s represent regions) from sector i in region r to sector j in region s, and x_j^s is the total input of sector j in region s. A^{rs} is an intermediate consumption matrix. Therefore, the MRIO evaluation can be expressed as

$$x = Ax + Y \tag{3}$$

and

$$x = (I - A)^{-1}Y \tag{4}$$

where $(I-A)^{-1}$ is the Leontief inverse matrix, showing the integrated inputs (covering direct and indirect products) required to fulfill one unit of final demand, and I stands for the identity matrix with the same scale as matrix A. Moreover, an environmental extended MRIO model associated with emissions or resources in each region (P_r) can be calculated as:

$$P_r = k_r (I - A)^{-1} Y^r \tag{5}$$

where P_r represents total emissions or resource consumption needed to satisfy the requirements of the production of goods and services throughout the entire supply chain driven directly and indirectly by the final demands, and k_r is a coefficient vector of resource or emissions consumption per unit of economic output in different economic sectors in region r.

2.2. Linkage analysis

Linkage analysis has been modified as the Hypothetical Extraction Method, which extracts a specific sector from the entire economic system and then assesses the role of that economic sector in terms of the integrated imports or exports [26,27]. It includes four elements of influence: the internal effect (IE), mixed effect (ME), net or external backward linkage (NBL), and net or external forward linkage (NEL).

The A matrix, Leontief matrix, final demand matrix, and coefficient vector of emissions or resource consumption can be expressed as:

$$A = \begin{pmatrix} A_{S,S} & A_{S,-S} \\ A_{-S,S} & A_{-S,-S} \end{pmatrix} \tag{6}$$

$$(I-A)^{-1} = \begin{pmatrix} A_{S,S} & A_{S,-S} \\ A_{-S,S} & A_{-S,-S} \end{pmatrix} \tag{7}$$

$$Y = \begin{pmatrix} y_{s,s} & y_{s,-s} \\ y_{-s,s} & y_{-s,-s} \end{pmatrix}, \tag{8}$$

and

$$K = \begin{pmatrix} k_s \\ k_{-s} \end{pmatrix} \tag{9}$$

where s is the target region of the economy and $-s$ is the combination of the remaining regions of the economy.

(1) The IE concerns the embodied resources or emissions produced and traded exclusively within a region, i.e., the resource consumption/emissions caused by the economic activities correlated only with the region itself:

$$\mathrm{IE} = k_s(I-A_{s,s})^{-1}y_s. \tag{10}$$

(2) The ME concerns the embodied resources or emissions produced by a region and sold back to that region via trade with other regions, i.e., the resource consumption/emissions correlated with the economic activities originally exported from the target region, which flow to other regions before finally flowing back to the region of concern:

$$\mathrm{ME} = k_s[\Delta_{s,s}-(I-A_{s,s})^{-1}]y_s \tag{11}$$

(3) The NBL (net import of resources) considers the resources and emissions embodied in products consumed outside the region, which are then purchased in that region to satisfy its requirement, i.e., the resource consumption/emissions embodied in the products imported from other regions to support the development of the target region:

$$\mathrm{NBL} = k_{-s}\Delta_{-s,s}y_s. \tag{12}$$

(4) The NFL (net export of resources) considers the resources and emissions embodied in products produced within a region, which are traded to other regions and never return, i.e., the resource consumption/emissions embodied in the products exported from the target region to meet the requirement of other regions:

$$\mathrm{NFL} = k_s\Delta_{s,-s}y_{-s}. \tag{13}$$

(5) The vertically integrated consumption (vertically integrated effect; VIE) is the total consumption of resources needed directly and indirectly to fulfill the requirements of the region, including domestic consumption and imports from other regions needed to meet the requirements of the target region's final demand:

$$\mathrm{VIE} = \mathrm{IE} + \mathrm{ME} + \mathrm{NBL} \tag{14}$$

(6) The horizontal integrated production (horizontal integrated effect; HIE) is the direct utilization of resources in the target region needed to satisfy the national final demand:

$$\mathrm{HIE} = \mathrm{IE} + \mathrm{ME} + \mathrm{NFL} \tag{15}$$

Further detailed explanation of each linkage indicator is provided in Table 1. IE-Water reflects the indicator IE with respect to scarce water consumption, similar to ME-Water, NFL-Water, NBL-Water, HIE-Water, and VIE-Water. IE-CO_2 shows the indicator IE in terms of CO_2 emissions, similar to ME-CO_2, NFL-CO_2, NBL-CO_2, HIE-CO_2, and VIE-CO_2. IE (Water/CO_2) means the ratio of IE-Water over IE-CO_2, reflecting the correlation between scarce water consumption and CO_2 emissions, similar to ME(Water/CO_2), NFL(Water/CO_2), NBL(Water/CO_2), HIE (Water/CO_2), and VIE(Water/CO_2).

2.3. Data collection

The 2012 China MRIO Table that includes 30 provinces (excluding Tibet, Taiwan, Hong Kong, and Macau) was used in this study. The basic data were collected from National IO Tables of China 2012 [33] and Regional IO Tables of China 2012 [34]. The MRIO table was constructed based on the 30 regional IO tables and estimated interregional trade flows. The import and export data of each province were used to calculate the interregional trade flow matrix of the MRIO table using a hybrid technique based on maximum entropy and a gravity model [35–37]. The MRIO table was calibrated using China's National IO Table 2012 using an RAS method, setting the values of national IO as the calibration of the total amount, and the provincial trade flows from the MRIO as the matrix structure. Detailed explanation of the construction of the MRIO 2012 can be found in previous studies [38–40].

CO_2 emission data were obtained from the China Emission Accounts & Datasets of 2012 for 45 sectors [41]. The classification of the CO_2 emission inventory and the sectoral classification of the MRIO 2012 table were different. The concordance matrix matched emissions from different classifications and reallocated the emissions to each sector in proportion to economic scale [42]. The sectoral water withdrawal data for each province were collected from the China Economic Census Yearbook [43] and the China Water Resources Bulletin [44]. Here, water consumption refers to the amount of withdrawn blue water that does not return to the ecosystem during a given period. The ratio of water consumption to water withdrawal is observed in each river basin and for each sector [9]; therefore, water consumption could be calculated by multiplying the water withdrawal data by the ratio of water consumption to water withdrawal. The notion of water stress is generally regarded as the proportion of total freshwater withdrawals to hydrological attainability [9,45]. The water stress index (WSI) is calculated to categorize water stress levels from no stress (WSI = 0) to maximum stress (WSI = 1) [46]. We used the WSI calculated by Feng et al. [9] for each province in China. The scarce water consumption calculation was performed by multiplying the provincial freshwater consumption with the WSI to reflect the impact of consumption on water stress. Then, the scarce water intensity coefficient was calculated based on the scarce water consumption over the total economic output of each sector in each province. Table 2 presents the basic information of economic development, scarce water consumption, and CO_2 emissions of each region in China.

3. Results

3.1. Linkage analysis for scarce water consumption

The scarce water consumption in each region of China is shown in Fig. 1 with the map shaded according to WSI values. It can be seen that regions with no stress or moderate stress of the water resource, e.g., Guangdong and Zhejiang provinces, still consume large amounts of scarce water resources. This is because although domestic production in these regions might not consume abundant quantities of the local scarce water, such regions import substantial amounts of products embodied with scarce water resources consumed in regions facing extreme water stress conditions. Regions with severe or extreme water stress conditions, e.g., Xinjiang, Shandong, Jiangsu, and Hebei provinces, also consume substantial quantities of local scarce water resources, instead of importing fewer scarce-water-intensive goods produced in regions with abundant water resources. Regions with severe or extreme water stress conditions, e.g., Xinjiang, Shandong, Jiangsu, and Hebei provinces, will import products from regions with no or moderate water stress conditions. Meanwhile, regions with abundant water resources, e.g., Guangdong and Zhejiang provinces, can export water-intensive goods to other regions, instead of outsourcing water resources to regions with shortages of water resources.

The information shown in Fig. 2 and Table 3 provides a detailed

Table 1
The explanation of indicators for linkage analysis.

Acronyms	Indicator	Explanation	Example
IE	Internal Effect	Representing the products produced, sold and purchased exclusively inside the same sector or region	Part of wheats, produced from agricultural sector, is kept as seeds for next year's production
ME	Mixed Effect	Representing the products sold out of the region, and then re-purchased by the original sector or region. It has dual features of forward and backward linkage	The iron ore is mined by the metal mining sector, manufactured by the metal smelting sector, metal products sector and general equipment, and then sold back to the original sector (metal mining sector), using as mining equipment
NBL	Net Backward Linkage	Representing the products imports from other sector or region to satisfy the final demand of the target sector or region, i.e., the net imports to the target sector in order to fulfill its final demand	For agriculture sector, the NBL is the imports from the rest economy (sectors excluding agricultural sector) to fulfill the final demand of agricultural sector
NFL	Net Forward Linkage	Representing the products exports to other sector or regions to satisfy the final demand of the rest economy, i.e., the net exports from the target sector in order to obtain the rest economy's demand	For agricultural sector, the NFL is the exports to other sectors to fulfill the final demand of the rest economy
VIE	Vertically Integrated Effect	Representing the direct and indirect requirements associated with the final demand of target sector or region, i.e., whether the products are utilized by the sector or region itself, or whether other sectors or regions processing them on its behalf	For agricultural sector, the VIE is the direct or indirect productions driven by its final requirements
HIE	Horizontal Integrated Effect	Representing the gross production of the target sector	For agricultural sector, the HIE is its total production to satisfy the final demands of the whole economy

Table 2
Economic development states, scarce water consumption intensity, water stress index, CO_2 emission intensity and reduction targets of each province and municipalities of China.

	GDP/capita Yuan/person	Int(SW) $m^3/10^3$ yuan	WSI	Int(CO_2) g/yuan	CO_2 intensity reduction target in 2020 compared with 2016
Beijing	60,096	1.40	1.00	111	−20.50%
Tianjin	47,970	2.63	1.00	205	−20.50%
Hebei	19,662	9.95	1.00	459	−20.50%
Shanxi	17,805	6.50	1.00	593	−18%
Inner Mongolia	26,521	11.11	0.66	522	−17%
Liaoning	26,057	4.34	0.58	344	−18%
Jilin	19,383	1.12	0.13	322	−18%
Heilongjiang	18,580	2.47	0.12	258	−17%
Shanghai	62,041	1.89	1.00	160	−20.50%
Jiangsu	33,837	7.27	0.94	206	−20.50%
Zhejiang	36,676	2.33	0.47	184	−20.50%
Anhui	12,039	0.39	0.03	274	−18%
Fujian	25,582	1.21	0.18	181	−19.50%
Jiangxi	13,322	0.53	0.03	239	−19.50%
Shandong	27,604	4.91	1.00	274	−20.50%
Henan	16,012	4.19	0.61	289	−19.50%
Hubei	16,386	0.31	0.03	276	−19.50%
Hunan	14,869	0.37	0.03	232	−18%
Guangdong	33,272	0.52	0.11	140	−20.50%
Guangxi	12,277	0.62	0.03	234	−17%
Hainan	14,923	0.48	0.03	195	−12%
Chongqing	16,629	0.13	0.02	196	−19.50%
Sichuan	12,963	0.79	0.10	222	−19.50%
Guizhou	7878	0.29	0.02	560	−18%
Yunnan	10,609	0.42	0.03	327	−18%
Shaanxi	15,546	5.06	0.69	258	−18%
Gansu	10,614	23.69	0.89	428	−17%
Qinghai	14,507	12.66	0.67	319	−12%
Ningxia	15,142	28.26	0.99	690	−17%
Xinjiang	16,999	88.55	0.96	353	−12%

Notes: Int(SW) and Int(CO_2) stand for scarce water consumption intensity and CO_2 emission intensity respectively.

explanation of scarce water consumption in each region of China. The HIEs-Water, i.e., production-based scarce water consumption in Xinjiang, Jiangsu, Hebei, and Shandong provinces are high, and the summation of their HIEs-Water accounts for 59% of national total scarce water utilization, despite these four regions having extreme water stress conditions. Furthermore, the water utilization in such regions is not only for the requirements of local final demands but also driven by consumption in other regions. As the NFLs-Water of these regions account for 30–42% of the HIEs-Water, such regions are major scarce water exporters. These regions are also ranked with the highest VIEs-Water levels. However, although Xinjiang and Hebei provinces have extreme water stress conditions, their scarce water NFLs-Water (exports) are higher than the NBLs-Water (imports), indicating that Xinjiang and Hebei provinces mainly export water resources to other regions, while other provinces support the lesser efforts in water conservation of such regions.

Guangdong, Zhejiang, Shandong, Jiangsu, and Shanghai are the top five importers of scarce water from other regions, implying they require large amounts of water resources from regions already under severe water stress conditions. It should be noted that Guangdong and Zhejiang provinces have moderate or even no water stress condition. Although their direct water consumptions (HIE-Water) are reasonably low, they import large amounts of products from regions that consume considerable scarce water resources; thus, transferring water stress to water scarce regions.

Xinjiang and Hebei provinces are the major exporters of scarce water under extreme water stress conditions. The pillar economic sector is agriculture in Xinjiang Province, while both the agricultural and industrial sectors are important in Hebei Province. These two provinces are comparatively less affluent than other regions and they tend to develop resource-intensive but low-tech and less-value-added economic sectors. Therefore, it is important to transfer the economic development of such regions to a high-tech mode that is less resource-intensive.

Guangdong, Zhejiang, and Shanghai are the major importers of scarce water under no or moderate water stress conditions. These wealthier regions import scarce water resources from other regions to support their own development, although they own abundant water resources. They tend to develop high-tech industries that are less resource-intensive but with high value-added. The government should encourage such regions to export high-tech development to other provinces to adjust the scarce water imports from regions under moderate water stress conditions, instead of transferring water pressure to regions under extreme water stress conditions.

3.2. Linkage analysis for CO_2 emissions

The CO_2 emission conditions in each region of China are shown in Fig. 3. The consumption-based CO_2 emissions (VIEs-CO_2) in regions such as Guangdong, Jiangsu, Zhejiang, Shanghai, and Beijing are high but their production-based CO_2 emissions (HIEs-CO_2) are comparatively low, implying these affluent regions mainly transfer their CO_2 emission pressure to other regions of China. Conversely, less affluent regions such as Hebei, Inner Mongolia, Henan, and Shanxi generate

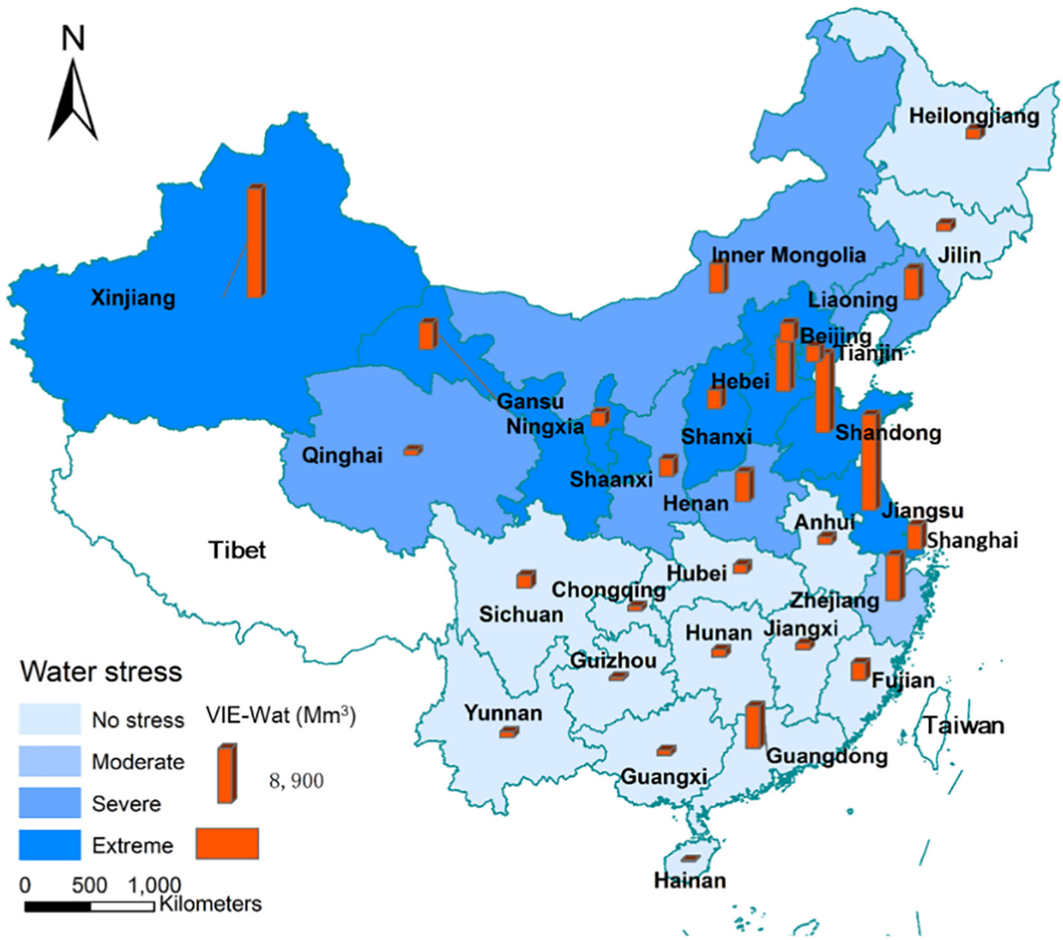

Fig. 1. Scarce water consumption in China. *Notes*: The map is shaded according to the water stress condition of each region in China, and the bar charts show the vertical integrated scarce water consumption of each region.

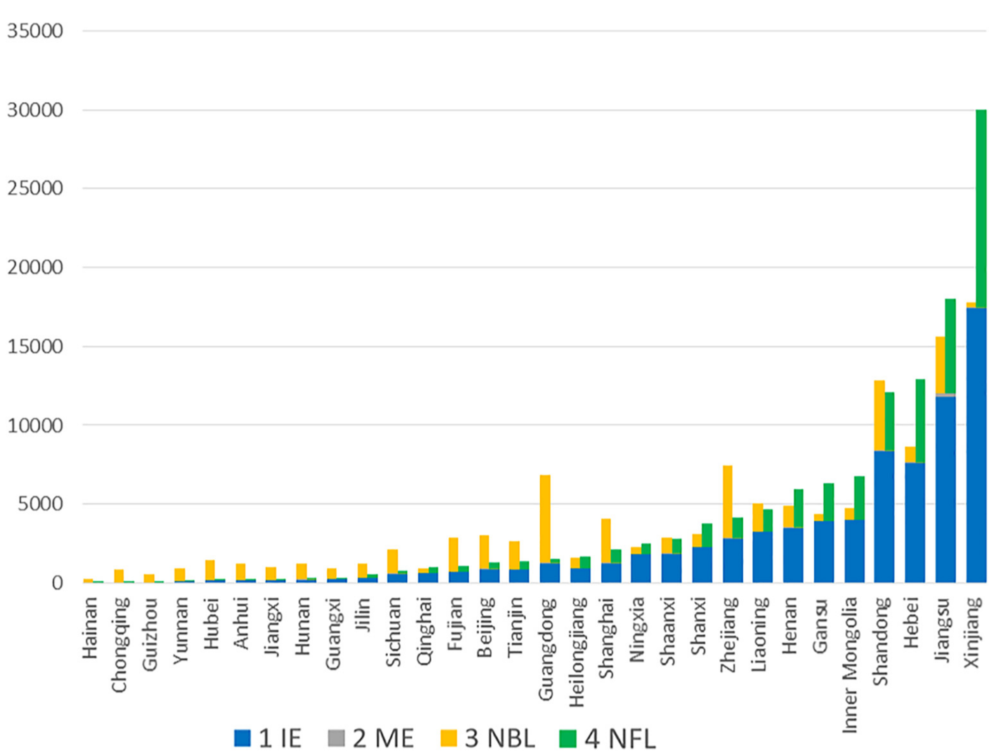

Fig. 2. Linkage analysis for scarce water consumption (Mm^3/yr) in 30 regions of China. Notes: For each region, the left-side bar shows VIE-Water (VIE = IE + ME + NBL), i.e. consumption-based scarce water utilization, including domestic water consumption and imports of embodied water resources driven by local final demand; the right-side bar shows HIE-Water (HIE = IE + ME + NFL), i.e. production-based scarce water utilization, including local scarce water utilization in target region to meet the national final demand. The bar charts are ranked according to the HIE-Water value of each region.

Table 3
The results of linkage analysis for scarce water.

	IE Mm^3	ME Mm^3	NBL Mm^3	NFL Mm^3	VIE Mm^3	HIE Mm^3	DE Mm^3	DE/IE	NFL/DE	NBL/DE
Beijing	884	10	2150	442	3044	1336	1374	1.55	0.32	1.57
Tianjin	825	6	1789	520	2620	1351	1405	1.70	0.37	1.27
Hebei	7588	83	970	5269	8641	12,940	13,579	1.79	0.39	0.07
Shanxi	2274	13	783	1508	3071	3795	3924	1.73	0.38	0.20
Inner Mongolia	3987	23	731	2734	4741	6744	7084	1.78	0.39	0.10
Liaoning	3242	20	1775	1380	5037	4642	4862	1.50	0.28	0.37
Jilin	323	2	877	239	1202	564	593	1.84	0.40	1.48
Heilongjiang	926	6	700	740	1632	1672	1757	1.90	0.42	0.40
Shanghai	1251	21	2796	865	4067	2136	2182	1.74	0.40	1.28
Jiangsu	11,819	216	3567	5946	15,602	17,982	18,764	1.59	0.32	0.19
Zhejiang	2828	36	4620	1268	7484	4132	4318	1.53	0.29	1.07
Anhui	167	1	1074	109	1242	278	290	1.74	0.38	3.70
Fujian	729	5	2113	330	2847	1064	1111	1.52	0.30	1.90
Jiangxi	186	1	831	106	1017	292	306	1.65	0.35	2.71
Shandong	8362	81	4395	3623	12,838	12,066	12,699	1.52	0.29	0.35
Henan	3500	32	1342	2452	4874	5984	6274	1.79	0.39	0.21
Hubei	173	1	1246	101	1420	276	290	1.67	0.35	4.30
Hunan	218	1	1028	117	1247	336	353	1.62	0.33	2.92
Guangdong	1258	13	5594	287	6866	1558	1620	1.29	0.18	3.45
Guangxi	219	1	696	126	916	346	363	1.66	0.35	1.92
Hainan	33	0	211	25	244	58	61	1.83	0.41	3.48
Chongqing	40	0	796	19	835	59	61	1.53	0.32	13.12
Sichuan	591	3	1536	197	2130	791	828	1.40	0.24	1.86
Guizhou	53	0	485	28	538	81	85	1.59	0.33	5.74
Yunnan	141	0	822	52	963	194	203	1.44	0.26	4.06
Shaanxi	1859	9	974	946	2842	2814	2947	1.59	0.32	0.33
Gansu	3906	11	456	2384	4373	6300	6581	1.69	0.36	0.07
Qinghai	660	1	247	317	908	977	1014	1.54	0.31	0.24
Ningxia	1805	2	448	697	2255	2504	2610	1.45	0.27	0.17
Xinjiang	17,392	63	344	12,567	17,799	30,022	31,536	1.81	0.40	0.01

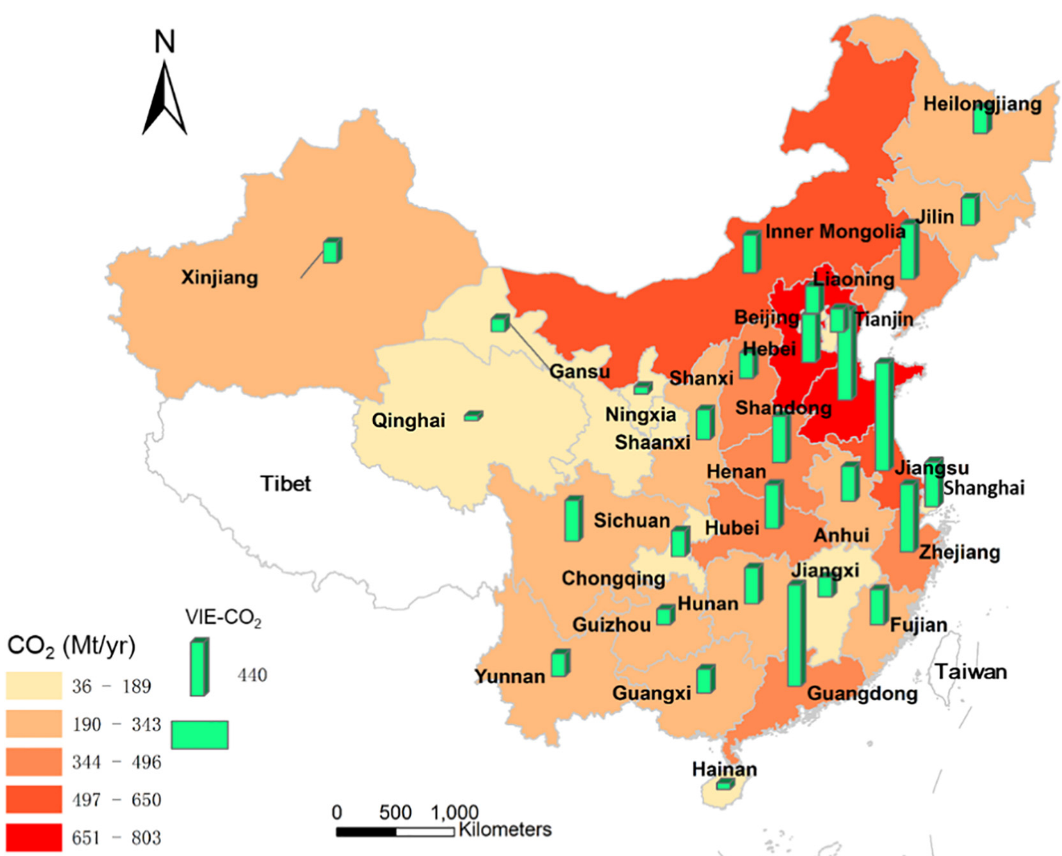

Fig. 3. Consumption-based CO_2 emissions and production-based CO_2 emissions in each region of China. *Notes*: The map is shaded according to the production-based carbon emission (HIE-CO_2) of each region in China, and the bar chart shows the consumption-based CO_2 emission (VIE-CO_2) of each region.

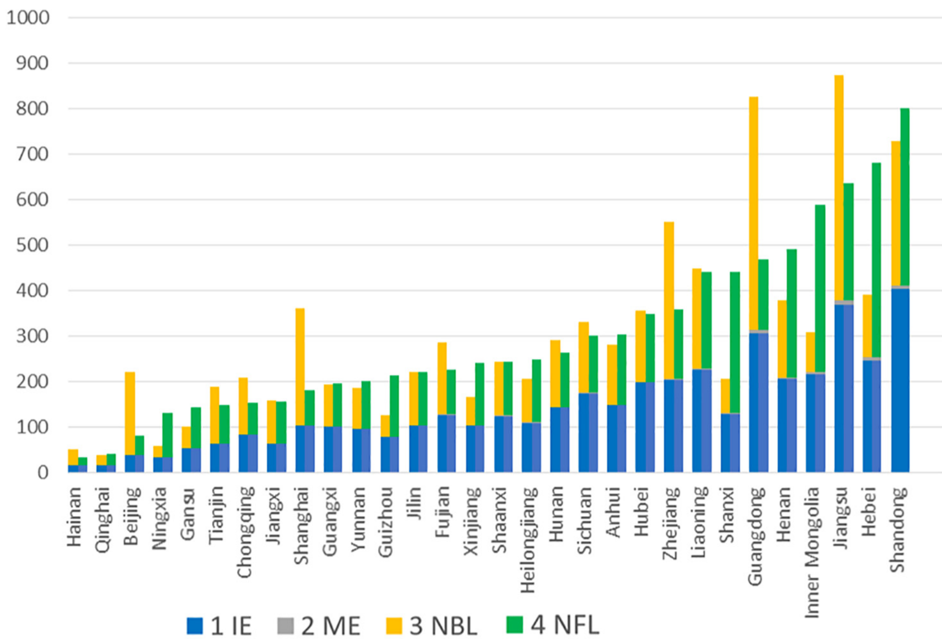

Fig. 4. Linkage analysis for CO_2 emissions (Mt/yr) in 30 regions of China. *Notes*: For each region, the left-side bar shows VIE-CO_2 (VIE = IE + ME + NBL), i.e. consumption-based CO_2 emissions, including domestic and imports of embodied CO_2 emissions driven by local final demand; the right-side bar shows HIE-CO_2 (HIE = IE + ME + NFL), i.e. production-based CO_2, including local CO_2 emissions in target region to meet the national final demand. The bar charts are ranked according to the HIE-CO_2 value of each region.

large amounts of CO_2 emissions (HIEs-CO_2) to support the national final demand, while their consumption-based CO_2 emissions (VIEs-CO_2) are comparatively low.

Detailed analyses of both production-based CO_2 emissions (HIEs-CO_2) and consumption-based CO_2 emissions (VIEs-CO_2) in each region of China are provided in Fig. 4 and Table 4. The IEs-CO_2 (inside effects, i.e., consumption of products with emissions generated in the local region) in the provinces of Shandong, Jiangsu, Guangdong, Hebei, and Liaoning are high, meaning these provinces are partly self-supporting in the production of emission-intensive products to satisfy their final demands. The HIEs-CO_2, i.e., production-based CO_2 emissions of Shandong, Hebei, Jiangsu, Inner Mongolia, and Henan are reasonably high. However, it should be noted that 63% and 62% of the HIEs-CO_2 of Hebei and Inner Mongolia, respectively, comprise NFLs-CO_2, implying these provinces mainly export emission-intensive production to satisfy the consumption in other regions. The VIEs-CO_2, i.e., consumption-based CO_2 emissions of Jiangsu, Guangdong, Shandong, Zhejiang, and Liaoning are reasonably high, while 57–62% of the VIEs-CO_2 of Jiangsu, Guangdong, and Zhejiang consist of NBLs-CO_2, illustrating these provinces mainly transfer their emission pressure to other regions

Table 4
The results of linkage analysis for CO_2 emission.

	IE Mt	ME Mt	NBL Mt	NFL Mt	VIE Mt	HIE Mt	DE Mt	DE/IE	NFL/DE	NBL/DE
Beijing	39	1	183	42	223	82	82	2.13	0.51	2.22
Tianjin	64	1	124	86	189	151	152	2.38	0.57	0.82
Hebei	248	5	140	429	393	682	686	2.76	0.63	0.20
Shanxi	129	3	76	311	207	443	446	3.47	0.70	0.17
Inner Mongolia	218	4	87	369	309	590	596	2.73	0.62	0.15
Liaoning	226	4	219	213	448	442	446	1.97	0.48	0.49
Jilin	104	1	116	116	221	222	224	2.15	0.52	0.52
Heilongjiang	111	1	96	137	208	249	253	2.29	0.54	0.38
Shanghai	104	2	257	77	363	183	185	1.77	0.42	1.39
Jiangsu	370	10	495	257	875	636	641	1.73	0.40	0.77
Zhejiang	204	4	344	151	552	359	362	1.78	0.42	0.95
Anhui	148	2	132	155	283	305	308	2.07	0.50	0.43
Fujian	128	1	159	98	288	227	229	1.79	0.43	0.69
Jiangxi	65	1	95	92	160	158	158	2.43	0.58	0.60
Shandong	404	10	316	390	729	803	812	2.01	0.48	0.39
Henan	206	4	169	282	378	492	496	2.40	0.57	0.34
Hubei	199	2	156	148	357	349	352	1.77	0.42	0.44
Hunan	144	1	146	120	292	265	268	1.85	0.45	0.54
Guangdong	307	8	513	155	827	470	473	1.54	0.33	1.08
Guangxi	102	1	92	94	195	197	198	1.94	0.48	0.47
Hainan	17	0	35	19	52	36	36	2.18	0.53	0.97
Chongqing	84	1	125	70	210	154	156	1.85	0.45	0.80
Sichuan	175	2	155	126	332	302	305	1.75	0.41	0.51
Guizhou	79	1	47	134	127	215	216	2.72	0.62	0.22
Yunnan	96	1	89	105	186	202	203	2.11	0.52	0.44
Shaanxi	125	2	118	119	245	245	248	1.99	0.48	0.48
Gansu	55	0	47	88	103	144	145	2.61	0.61	0.32
Qinghai	18	0	21	23	39	41	42	2.30	0.55	0.50
Ningxia	35	0	24	96	59	132	133	3.78	0.73	0.18
Xinjiang	105	1	63	136	168	242	245	2.35	0.56	0.26

instead of choosing self-supporting development modes. The NFLs-CO_2, i.e., the exports of embodied CO_2 emissions of Hebei, Shandong, Inner Mongolia, Shanxi, and Henan rank in the top 5 out of the 30 regions in China, and their NFLs-CO_2 account for 50–70% of the HIEs-CO_2. In particular, Shanxi's NFL-CO_2 accounts for 70% of its total CO_2 emissions, indicating that it is a major exporter of emission-intensive products in support of national development. The NBLs-CO_2 of Guangdong, Jiangsu, Zhejiang, Shandong, and Shanghai are reasonably high, and for Shanghai, Guangdong, and Zhejiang, the NBLs-CO_2 account for 71%, 62%, and 62% of their VIEs-CO_2 respectively, illustrating these comparatively affluent regions tend to import pollution-intensive products from other regions. Beijing, Shanghai, Guangdong, Zhejiang, and Jiangsu have the highest values of NBL/NFL-CO_2 ratios (1.9–4.3); implying these wealthier regions mainly import pollution-intensive products from other regions, while generating fewer emissions in support of the consumption of other regions. Conversely, Inner Mongolia, Shanxi, Ningxia, Hebei, and Guizhou have low levels of NBL/NFL-CO_2 ratios (0.2–0.3), meaning these comparatively less-developed regions emit more CO_2 emissions in manufacturing products to support the final demands of the other regions.

3.3. Water-carbon nexus in 30 regions of China

3.3.1. IE(Water/CO_2)

The provinces of Xinjiang, Jiangsu, Shandong, Hebei, and Inner Mongolia have high values of IE-Water, and Shandong, Jiangsu, Guangdong, Hebei, and Liaoning provinces have large values of IE-CO_2. It is remarkable that the provinces of Shandong, Jiangsu, and Hebei are major water-carbon nexus nodes, because these provinces not only utilize large amounts of scarce water resources but also discharge huge amounts of CO_2 emissions to support their development. The values of IE(Water/CO_2) in provinces such as Xinjiang, Gansu, Ningxia, and Qinghai are reasonably high, implying these provinces consume large amounts of scarce water resources but generate low CO_2 emissions. This is because these regions are under severe water stress conditions. Conversely, the values of IE(Water/CO_2) in provinces such as Yunnan, Anhui, Hubei, Guizhou, and Chongqing are comparatively low because these regions are mainly under the condition of no water stress.

3.3.2. NFL(Water/CO_2)

The NFLs comparison of water resources and CO_2 emissions is presented in Fig. 5, and the ratio NFL(Water/CO_2) of NFL-Water over NFL-CO_2 is given in Table 5. Regions with large values of NFL-Water include Xinjiang, Jiangsu, Hebei, Shandong, and Inner Mongolia, while regions with large values of NFL-CO_2 include Hebei, Shandong, Inner Mongolia, Shanxi, and Henan. It should be noted that regions such as Shandong, Inner Mongolia, and Hebei not only have high values of NFL-Water but also large values of NFL-CO_2, implying they are in development modes involving intensive resource consumption and severe pollution discharge. Furthermore, they are under extreme water stress conditions and they have strict CO_2 reduction targets (17.0–20.5%). It is therefore urgent that these regions transform their industrial structures toward modes incorporating resource conservation and reduced pollution. The high values of NFL(Water/CO_2) for Xinjiang, Gansu, Jiangsu, and Qinghai provinces, imply these regions mainly export products embodied with large amounts of scarce water resources and comparatively low CO_2 emissions. This is because these regions are under extreme water stress conditions. The provinces with low values of NFL(Water/CO_2) are Guizhou, Chongqing, Yunnan, and Hubei, which export fewer scarce water resources to other regions, while exporting products with more embodied CO_2 emissions. The correlation between NFL-Water and NFL-CO_2 is not strong because the different regions are under various water stress conditions (Fig. 6).

3.3.3. NBL(Water/CO_2)

The correlation between NBL-Water and NBL-CO_2 of each region in China is presented in Fig. 7. It shows that Guangdong, Jiangsu, Zhejiang, Shandong, and Shanghai are importers of scarce water resources and embodied CO_2 emissions, indicating the development of these provinces relies on the support of other regions. It should be mentioned that provinces such as Guangdong, Zhejiang, and Shanghai are under no or moderate water stress conditions, while still transferring water stress to other regions with severe water stress. The NBL(Water/CO_2) indicates the ratio of NBL-Water over NBL-CO_2, reflecting the correlation between imports of scarce water resources and embodied CO_2 emissions. It shows that the provinces of Ningxia, Tianjin, Shandong, Zhejiang, and Fujian have high values of NBL(Water/CO_2), indicating these provinces import more scarce water resources than embodied CO_2 emissions. Zhejiang and Fujian are under no or moderate water stress conditions; however, they still import large amounts of scarce water-intensive products. Provinces such as Xinjiang, Hainan, Chongqing, Hebei, and Hunan have low values of NBL(Water/CO_2) because they import products associated with more embodied CO_2 emissions but fewer scarce water resources. It should be noted that the provinces of

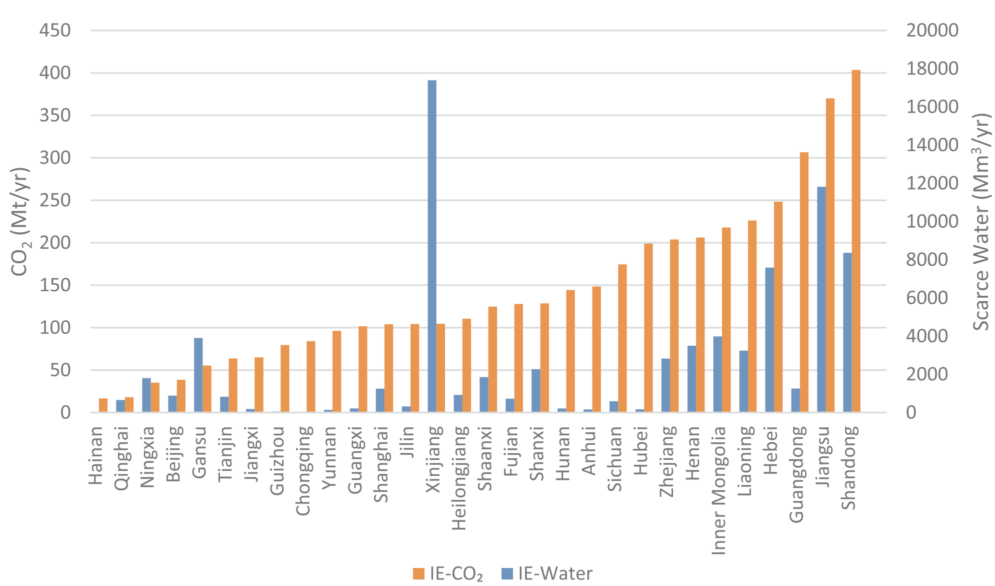

Fig. 5. IE of scarce water consumptions (Mm^3/yr) and CO_2 emissions (Mt/yr) of each region. Notes: IE (internal effect) stands for the products generated, sold and purchased exclusively in the same region. The bar charts are ranked according to the value of IE-CO_2.

Table 5
Linkage relations for scarce water consumption and CO_2 emissions.

	IE Water/CO_2	ME Water/CO_2	NBL Water/CO_2	NFL Water/CO_2	VIE Water/CO_2	HIE Water/CO_2	DE Water/CO_2
Beijing	1.61	0.71	0.83	0.74	0.96	1.15	1.17
Tianjin	0.91	0.37	1.01	0.43	0.98	0.63	0.65
Hebei	2.15	1.10	0.49	0.87	1.55	1.34	1.40
Shanxi	1.25	0.33	0.73	0.34	1.04	0.60	0.62
Inner Mongolia	1.29	0.40	0.59	0.52	1.08	0.80	0.84
Liaoning	1.01	0.39	0.57	0.46	0.79	0.74	0.77
Jilin	0.22	0.10	0.53	0.14	0.38	0.18	0.19
Heilongjiang	0.59	0.29	0.51	0.38	0.55	0.47	0.49
Shanghai	0.85	0.81	0.77	0.79	0.79	0.82	0.83
Jiangsu	2.25	1.57	0.51	1.63	1.26	1.99	2.06
Zhejiang	0.98	0.56	0.95	0.59	0.96	0.81	0.84
Anhui	0.08	0.04	0.57	0.05	0.31	0.06	0.07
Fujian	0.40	0.27	0.94	0.24	0.70	0.33	0.34
Jiangxi	0.20	0.08	0.62	0.08	0.45	0.13	0.14
Shandong	1.46	0.59	0.98	0.65	1.24	1.06	1.10
Henan	1.20	0.59	0.56	0.61	0.91	0.86	0.89
Hubei	0.06	0.04	0.56	0.05	0.28	0.06	0.06
Hunan	0.11	0.06	0.50	0.07	0.30	0.09	0.09
Guangdong	0.29	0.11	0.77	0.13	0.58	0.23	0.24
Guangxi	0.15	0.08	0.53	0.09	0.33	0.12	0.13
Hainan	0.14	0.07	0.42	0.09	0.33	0.11	0.12
Chongqing	0.03	0.02	0.45	0.02	0.28	0.03	0.03
Sichuan	0.24	0.09	0.70	0.11	0.45	0.18	0.19
Guizhou	0.05	0.01	0.73	0.01	0.30	0.03	0.03
Yunnan	0.10	0.03	0.65	0.04	0.36	0.07	0.07
Shaanxi	1.05	0.40	0.58	0.56	0.82	0.81	0.84
Gansu	4.97	1.66	0.69	1.91	3.00	3.09	3.20
Qinghai	2.56	0.72	0.84	0.96	1.64	1.67	1.71
Ningxia	3.62	0.34	1.32	0.51	2.68	1.34	1.39
Xinjiang	11.72	5.30	0.39	6.49	7.46	8.75	9.05

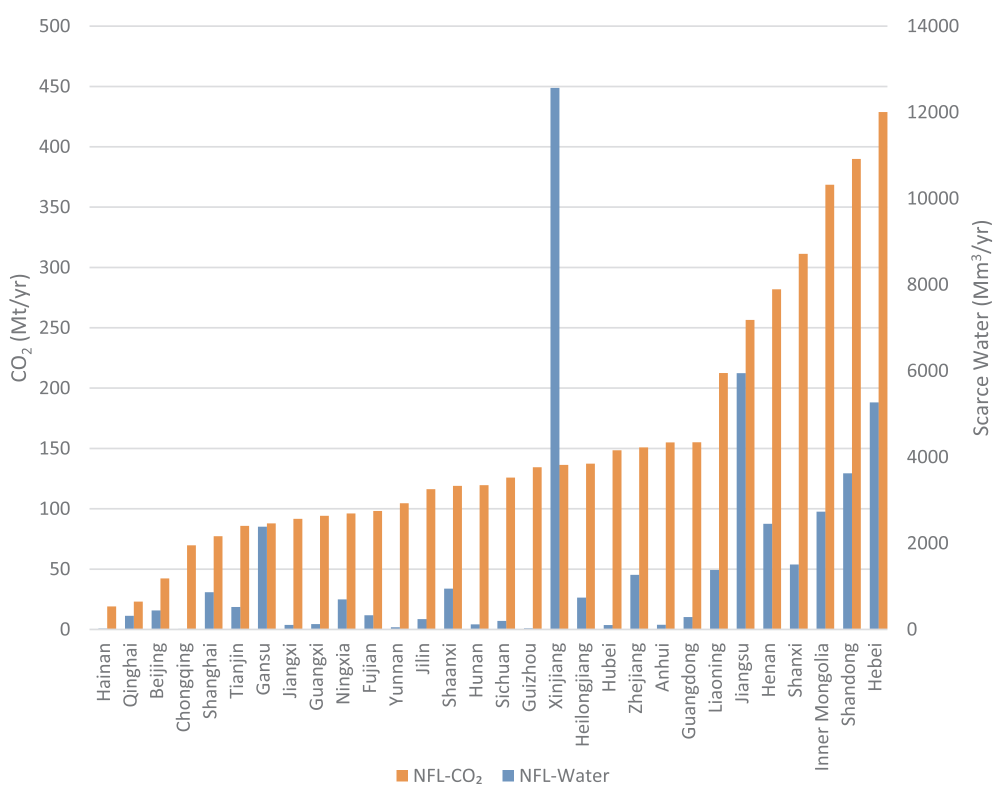

Fig. 6. NFL of scarce water consumptions (Mm^3/yr) and CO_2 emissions (Mt/yr) of each region. Notes: NFL (net forward linkage) stands for the products exporting to other regions to fulfill the final demands of the rest economy. The bar charts are ranked according to the value of NFL-CO_2.

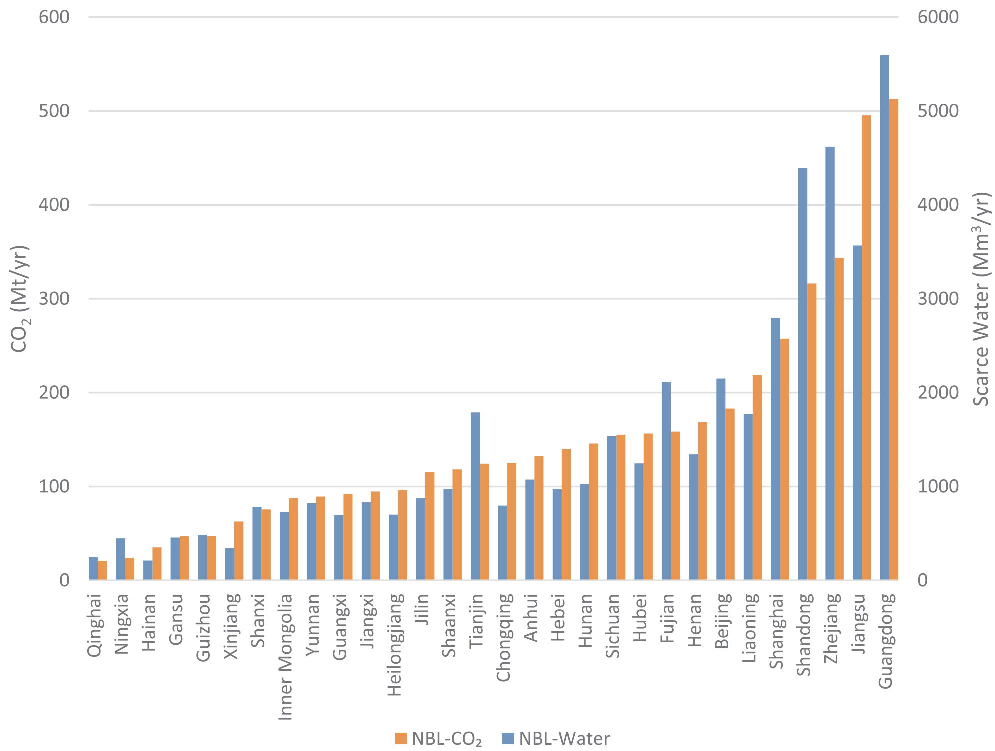

Fig. 7. NBL of scarce water consumptions (Mm^3/yr) and CO_2 emissions (Mt/yr) of each region. Notes: NBL (net backward linkage) stands for the production importing from other regions to obtain its own final demands. The bar charts are ranked according to the value of NBL-CO_2.

Xinjiang and Hebei are under extreme water stress conditions, demanding import products associated with water resources from regions with abundant water resources.

3.3.4. HIE(Water/CO_2)

The HIE of scarce water and CO_2 emission in each region of China are shown in Fig. 8. The provinces of Xinjiang, Jiangsu, Hebei, Shandong, and Inner Mongolia have high values of HIE-Water, while the provinces of Inner Mongolia, Jiangsu, Shandong, Hebei, and Henan have high values of HIE-CO_2. This shows that Shandong, Hebei, Jiangsu, and Inner Mongolia are important water-carbon nexus nodes for HIE, i.e., production-based scarce water consumption and CO_2 emissions. For these provinces, it would be effective to enact policies intended to reduce scarce water consumption and to restrict CO_2 emissions. Xinjiang, Gansu, Jiangsu, Qinghai, and Ningxia provinces have high values of HIEs(Water/CO_2), which imply these regions manufacture products with high scarce water consumption but low CO_2 emissions. As these regions are under severe water stress conditions, it is imperative that their production structures be oriented toward resource efficiency. The provinces of Yunnan, Anhui, Hubei, Chongqing, and Guizhou have low values of HIEs(Water/CO_2), meaning their generation of CO_2 emissions is greater than their consumption of scarce water resources.

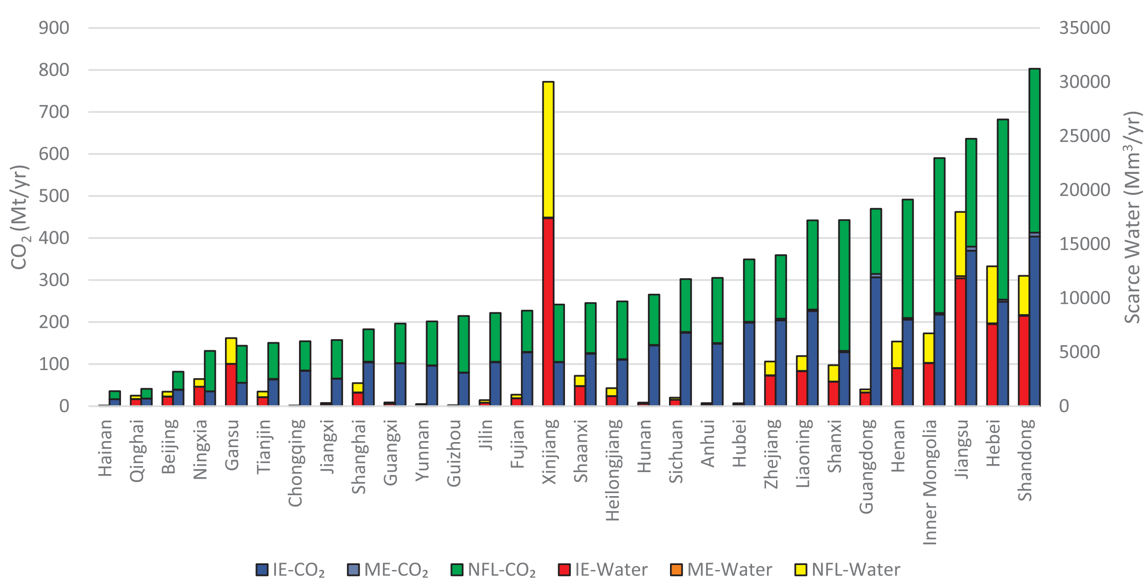

Fig. 8. HIE of scarce water consumptions (Mm^3/yr) and CO_2 emissions (Mt/yr) of each region. Notes: HIE (horizontal integrated effect): reflects the total scarce water consumption or CO_2 emissions of each region from production perspective, i.e., HIE = IE + ME + NFL. The bar charts are ranked according to the value of HIE-CO_2.

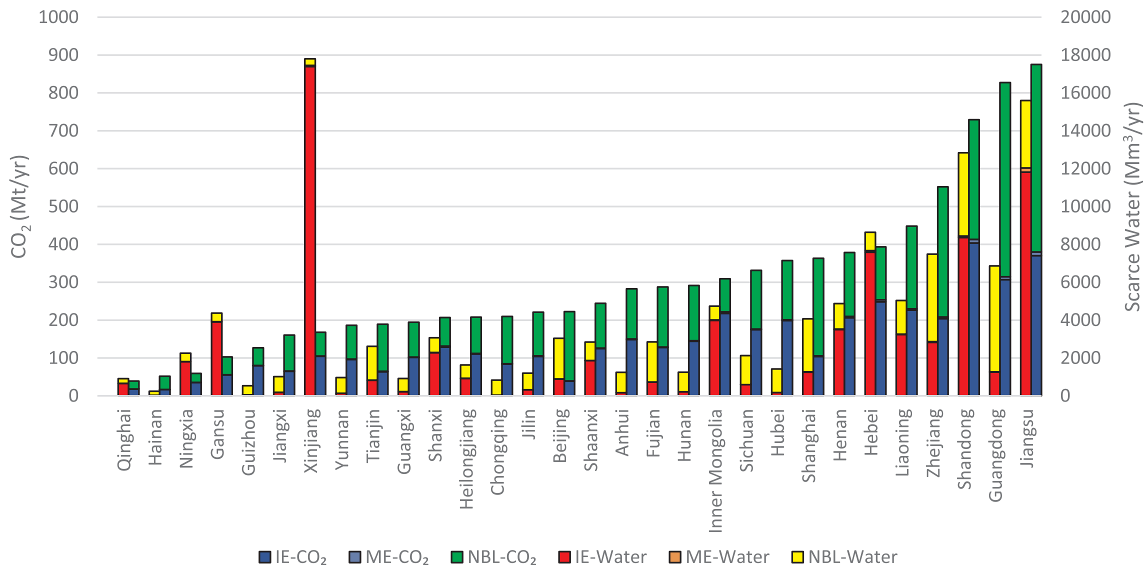

Fig. 9. VIE of scarce water consumptions (Mm^3/yr) and CO_2 emissions (Mt/yr) of each region. Notes: VIE (vertically integrated effect) reflects the total scarce water consumption or CO_2 emissions of each region from consumption perspective, i.e., VIE = IE + ME + NBL The bar charts are ranked according to the value of VIE-CO_2.

3.3.5. VIE(Water/CO_2)

The provinces of Xinjiang, Jiangsu, Shandong, Hebei, and Zhejiang have large values of VIEs-Water, while the provinces of Jiangsu, Guangdong, Shandong, Zhejiang, and Liaoning have high values of VIEs-CO_2, which indicate that Jiangsu, Shandong, and Zhejiang are the major water-carbon nexus nodes from the consumption perspective (Fig. 9). Furthermore, although Zhejiang Province is under moderate water stress conditions, it still imports large quantities of water-intensive products from regions under severe or extreme water stress conditions. Xinjiang, Gansu, Ningxia, and Qinghai have high values of the VIEs(Water/CO_2) indicator because they are mainly under severe or extreme water stress conditions and have fewer CO_2 intensive industries for economic development. Conversely, Anhui, Hunan, Guizhou, Chongqing, and Hubei provinces have low values of VIEs(Water/CO_2) because these regions are under no or moderate water stress conditions with less scarce water resource consumption.

3.4. Linkage relations for water-carbon nexus

Table 5 provides the ratios of scarce-water-related linkage indictors over CO_2-emission-related linkage indictors (Water/CO_2). The results show that Beijing, Tianjin, and Shanghai have high values of all indicators, meaning that these regions exert higher pressure on scarce water resources than on CO_2 emissions both internally and externally. These municipalities are developed regions under extreme water stress conditions with strict CO_2 intensity reduction targets (20.5% in 2020 compared with 2016). Because they tend to outsource their environmental pressure to the other regions, their water scarcity and CO_2 reduction requirements might aggravate such outsourcing conditions. Therefore, targeted policies should be enacted with consideration of the unequal transfer of environmental impact between regions along production chains.

Guangdong and Fujian provinces have low values for all indicators except NBL(Water/CO_2). This is because these two regions are under no water stress conditions; thus, the production-based environmental pressure on CO_2 is higher than on the scarce water resource. However, as developed regions, they tend to import products with huge environmental impacts from other economic regions. Such economic activities potentially transfer huge scarce water pressure to regions already under severe or even extreme water stress conditions.

Hebei, Jiangsu, and Gansu are provinces with high values for all indicators except NBL(Water/CO_2), which means these regions are under severe water stress conditions and have higher pressures on production-based water stress conditions than on CO_2 emissions. The NBL is comparatively lower than the average value. It should be noted that while these regions import products with less scarce water resources, they cannot alleviate the water stress conditions in the target region.

4. Discussion

The water-carbon nexus condition in each region of China is complex. As different regions face various water stress situations and CO_2 emission reduction targets, the integrated management of water resources and CO_2 controls needs a shift toward a nexus paradigm. Table 6 presents a summary of the results of the water-carbon nexus

Table 6
Important regions for the water-CO_2 nexus from the perspective of production-based linkage analysis.

	Water	CO_2	Water-CO_2 nexus
IE	Xinjiang Jiangsu Shandong Hebei Inner Mongolia	Shandong Jiangsu Guangdong Hebei Liaoning	Jiangsu Shandong Hebei
NFL	Xinjiang Jiangsu Hebei Shandong Inner Mongolia	Hebei Shandong Inner Mongolia Shanxi Henan	Hebei Shandong Inner Mongolia
HIE	Xinjiang Jiangsu Hebei Shandong Inner Mongolia	Shandong Hebei Jiangsu Inner Mongolia Henan	Jiangsu Hebei Shandong Inner Mongolia
Overlap	Xinjiang Jiangsu Shandong Hebei Inner Mongolia	Shandong Hebei	Shandong Hebei

Notes: Only top 5 provinces with high values of IE, NFL and HIE are listed on the table. The column of water-CO_2 nexus shows the overlap of regions between the column of water and CO_2, and last row shows the overlap of provinces in IE, NFL and HIE.

from the perspective of production-based linkage analysis. It shows that Jiangsu, Shandong, and Hebei are the major water-carbon nexus nodes for IE, indicating these provinces are self-supportive regions in terms of development. However, as these regions are under severe or extreme water stress conditions and stringent CO_2 emission reduction targets (20.5%), it would be better for these regions to increase their imports ratio to support their development. Hebei, Shandong, and Inner Mongolia are the major water-carbon nexus nodes for NFL, implying these provinces are important production exporters in support of the national development. Jiangsu, Hebei, Shandong, and Inner Mongolia are the major water-carbon nexus nodes for HIE, meaning these provinces are major producers of products associated with large amounts of scarce water resources and intensive CO_2 emissions. Xinjiang, Jiangsu, Shandong, Hebei, and Inner Mongolia are the major scarce water resource suppliers in China, as indicated by their high values of IE-Water, NFL-Water, and HIE-Water. The large values of IE-CO_2, NFL-CO_2, and HIE-CO_2 of Shandong and Hebei indicate these regions are major CO_2 emitters in relation to both satisfying the final demand and supporting the development of the nation. Accordingly, the important water-carbon nexus nodes from the perspective of production-based linkage analysis are Shandong and Hebei provinces, because they are important nodes for IE, NFL, and HIE; however, these two provinces are already under extreme water stress conditions and they have stringent CO_2 emission reduction targets (20.5%). Therefore, it is imperative these two provinces adjust their production structure toward a mode of resource conservation and lower emission intensity.

The summary of the water-carbon nexus from the perspective of consumption-based linkage analysis is shown in Table 7. It can be seen that Guangdong, Zhejiang, Shandong, Jiangsu, and Shanghai are the major water-carbon nexus nodes for NBL, which is because these provinces are major importers of scarce water resources and embodied CO_2 emissions from other regions to support their own development. Guangdong, Zhejiang, and Shanghai are under no or moderate water stress conditions; however, they import large quantities of products with embodied scarce water resources from regions under severe water stress conditions. Furthermore, as these regions have strict CO_2 emission reduction targets (20.5%), they might increase their CO_2 emission outsourcing to other regions. This would improve their NBL-CO_2 and unavoidably increase their NBL-Water, transferring additional pressure

Table 7
Important regions for the water-CO_2 nexus from the perspective of consumption-based linkage analysis.

	Water	CO_2	Water-CO_2 nexus
IE	Xinjiang Jiangsu Shandong Hebei Inner Mongolia	Shandong Jiangsu Guangdong Hebei Liaoning	Jiangsu Shandong Hebei
NBL	Guangdong Zhejiang Shandong Jiangsu Shanghai	Guangdong Jiangsu Zhejiang Shandong Shanghai	Guangdong Zhejiang Shandong Jiangsu Shanghai
VIE	Xinjiang Jiangsu Shandong Hebei Zhejiang	Jiangsu Guangdong Shandong Zhejiang Liaoning	Jiangsu Shandong
Overlap	Jiangsu Shandong	Shandong Jiangsu Guangdong	Jiangsu Shandong

Notes: Only top 5 provinces with high values of IE, NFL and HIE are listed on the table. The column of Water-CO_2 nexus shows the overlap of regions between the column of water and CO_2, and last row shows the overlap of provinces in IE, NFL and HIE.

on CO_2 emissions and scarce water consumption to other regions of China. Jiangsu and Shandong are the major water-carbon nexus nodes for VIE, implying they are the major consumers of products embodied with scarce water resources and intensive CO_2 emissions. From the consumption-perspective, Jiangsu and Shandong are the major scarce water resource consumers, and Shandong, Jiangsu, and Guangdong are the major consumers of production embodied with large CO_2 emissions. This reflects that Jiangsu and Shandong are the two major provinces for the water-carbon nexus from the perspective of consumption-based linkage analysis. Finally, Shandong Province is shown as the most important node of the water-carbon nexus along the national trade pathway from both production- and consumption-based perspectives.

The environmental pressures of water scarcity and intensive CO_2 emissions are highly correlated with production and income level. Three indicators derived from linkage analysis can facilitate understanding of the link between domestic consumption and environmental pressure outside of a region. Tables 8 and 9 present the results of scarce water consumption and CO_2 emission in China, as well as the equivalent results of water consumption in Spain [47] for comparison. The ratio of VIE/(IE + ME) reflects the water or CO_2 pressure transferred to other regions to satisfy domestic demand. The indicator of HIE/VIE informs the influence of trade on water consumption or CO_2 emissions, i.e., external pressures. The VIE/capita reflects the water or CO_2 pressure derived from population lifestyle.

The results show the average values of VIE/(IE + ME) in China are lower than in Spain, implying the regions of China exert less pressure on external regions. Four regions (total 17) in Spain have values of VIE/(IE + ME) > 10, while only 2 regions (total 30) in China have values > 10, i.e., Chongqing (21.04) and Guizhou (10.10). These regions are under no water stress conditions, while they import products embodied with large amounts of scarce water resources, thereby transferring water pressure to other regions. Beijing and Shanghai have high values of VIE/(IE + ME) in terms of CO_2 emissions, indicating they outsource huge amounts of CO_2 emissions to other regions. Hebei, Shanxi, and Inner Mongolia have low values of VIE/(IE + ME) in terms of both scarce water resources and CO_2 emissions, illustrating they exert less environmental pressure on other economic regions, while mainly relying on themselves to fulfill their final demands.

The regions with the highest values of the HIE/VIE ratio are Hebei, Shanxi, Inner Mongolia, and Henan. It means these regions mainly export products embodied with huge amounts of scarce water resources and CO_2 emissions to other regions, while importing less-water-intensive or less-CO_2-intensive products. It should be mentioned that these regions are under extreme water stress conditions and carbon-intensive development modes. Regions such as Beijing, Shanghai, Guangdong, and Zhejiang have low values of HIE/VIE in terms of both scarce water resources and CO_2 emissions, indicating these regions mainly outsource environmental pressures to other economic regions to satisfy their own final demands. The average value of HIE/VIE in China is higher than in Spain, suggesting that regions in Spain have stronger links to other regions through the exporting of products.

5. Conclusions

Linkage analysis provides a general approach for the evaluation of the role and position of individual regions and sectors along an entire production chain. In combination with water stress and CO_2 emission conditions in the various regions, this method can elucidate the responsibilities for water conservation and CO_2 reduction. The results of this study showed that Beijing, Tianjin, and Shanghai tend to import products from other regions to alleviate their own severe water stress conditions and to realize their decarbonization targets. However, such economic activities might transfer water stress pressure and additional CO_2 emission burdens to other regions. Conversely, it was found that provinces such as Hebei, Jiangsu, and Gansu, which are under severe water stress conditions and have ambitious carbon reduction targets,

Table 8
Indicators on the pressure exerted on water resources and CO_2 emissions by each region in China.

China	VIE/(IE + ME) Scarce water	VIE/(IE + ME) CO_2	HIE/VIE Scarce water	HIE/VIE CO_2	VIE/capita (m^3/capita) Scarce water	VIE/capita (t/capita) CO_2
Beijing	3.41	5.62	0.45	0.37	186	14
Tianjin	3.15	2.92	0.54	0.80	235	17
Hebei	1.13	1.55	1.57	1.74	124	6
Shanxi	1.34	1.57	1.28	2.16	91	6
Inner Mongolia	1.18	1.39	1.49	1.93	197	13
Liaoning	1.54	1.95	0.97	0.99	117	10
Jilin	3.70	2.09	0.49	1.01	44	8
Heilongjiang	1.75	1.86	1.08	1.22	43	5
Shanghai	3.20	3.43	0.54	0.51	219	20
Jiangsu	1.30	2.30	1.20	0.73	205	11
Zhejiang	2.61	2.65	0.58	0.66	148	11
Anhui	7.37	1.88	0.23	1.09	20	5
Fujian	3.88	2.23	0.39	0.80	79	8
Jiangxi	5.46	2.44	0.30	0.99	23	4
Shandong	1.52	1.77	0.99	1.11	137	8
Henan	1.38	1.80	1.29	1.31	52	4
Hubei	8.15	1.78	0.20	0.99	25	6
Hunan	5.69	2.00	0.28	0.92	20	5
Guangdong	5.40	2.63	0.24	0.57	73	9
Guangxi	4.16	1.90	0.40	1.02	19	4
Hainan	7.35	3.10	0.25	0.70	29	6
Chongqing	21.04	2.47	0.07	0.74	30	7
Sichuan	3.59	1.88	0.39	0.92	26	4
Guizhou	10.10	1.59	0.16	1.70	14	3
Yunnan	6.81	1.92	0.21	1.09	21	4
Shaanxi	1.52	1.93	1.04	1.01	76	7
Gansu	1.12	1.84	1.51	1.41	167	4
Qinghai	1.37	2.14	1.12	1.07	164	7
Ningxia	1.25	1.67	1.16	2.24	370	10
Xinjiang	1.02	1.59	1.77	1.46	850	8
Average	4.08	2.20	0.74	1.11	126.82	7.78

Note: VIE/(IE + ME) – Scarce water: Consumption-based scarce water/total uses of domestic scarce water.
HIE/VIE – Scarce water: Production-based scarce water/consumption-based scarce water.
VIE/capita – Scarce water: Per capita total consumption-based scarce water (m^3/capita).
VIE/(IE + ME) – CO_2: Consumption-based CO_2/total domestic CO_2.
HIE/VIE – CO_2: Production-based CO_2/consumption-based CO_2.
VIE/capita – CO_2: Per capita total consumption-based CO_2 (Mt/capita).

Table 9
Indicators on the pressure exerted on water resources by each region in Spain.

Spain	VIE/(IE + ME) Water	HIE/VIE Water	VIE/capita (m^3/capita) Water
Andalusia	2.24	2.19	924
Aragon	2.4	2.15	1917
Castile–La Mancha	1.66	3.25	1373
Asturias	4.21	0.67	713
Baleares	3.21	0.53	1354
Canarias	6.93	0.2	1097
Cantabria	7.87	0.56	1153
Castile and Leon	1.45	2.69	1306
Catalonia	7.75	0.39	1602
Galicia	3.76	0.77	1103
La Rioja	4.32	1.05	2115
Madrid	19.54	0.08	1837
Navarre	6.34	1.12	1963
Basque country	11.55	0.15	2061
Extremadura	11.41	1.66	1842
Murcia C and M	46.86	0.17	2331
Valencian C.	9.91	0.37	1358
Average	8.906471	1.058824	1532.294

Note: VIE/(IE + ME) – Water: Consumption-based scarce water/total uses of domestic water.
HIE/VIE – Water: Production-based scarce water/consumption-based scarce water.
VIE/capita – Water: Per capita total consumption-based scarce water (m^3/capita).

mainly consume local water resources and generate products with huge embodied CO_2 emissions.

The objective of this study was to provide new insights and to contribute to the discourse on water conservation and CO_2 emission reductions in China and globally. In future research, given the context of globalization, linkage analysis could serve as a promising approach with which to both decompose water consumption and CO_2 emission responsibilities to countries that are geographically dispersed but linked through global value chains, and to map the water-carbon nexus status of various countries within the global trading network.

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References

[1] Venkatesh G, Chan A, Brattebø H. Understanding the water-energy-carbon nexus in urban water utilities: comparison of four city case studies and the relevant influencing factors. Energy 2014;75:153–66.
[2] Stokes JR, Hendrickson TP, Horvath A. Save water to save carbon and money: developing abatement costs for expanded greenhouse gas reduction portfolios. Environ Sci Technol 2014;48:13583–91.

[3] Dodder RS, Barnwell JT, Yelverton WH. Scenarios for low carbon and low water electric power plant operations: implications for upstream water use. Environ Sci Technol 2016;50:11460–70.
[4] Fang DL, Chen B. Linkage analysis for the water–energy nexus of city. Appl Energy 2017;189:770–9.
[5] Li X, Feng KS, Siu YL, Hubacek K. Energy-water nexus of wind power in China: the balancing act between CO_2 emissions and water consumption. Energy Policy 2012;45:440–8.
[6] Ackerman F, Fisher J. Is there a water–energy nexus in electricity generation? Long-term scenarios for the western United States. Energy Policy 2013;59:235–41.
[7] Zhang C, Anadon LD, Mo HP, Zhao ZG, Liu Z. Water-carbon trade-off in China's coal power industry. Environ Sci Technol 2014;48:11082–9.
[8] Scott CA, Pierce SA, Pasqualetti MJ, Jones AL, Montz BE, Hoover JH. Policy and institutional dimensions of the water–energy nexus. Energy Policy 2011;39:6622–30.
[9] Feng KS, Hubacek K, Pfister S, Yu Y, Sun LX. Virtual scarce water in China. Environ Sci Technol 2014;48:7704–13.
[10] Feng KS, Davis SJ, Sun LX, Li X, Guan DB, Liu WD, et al. Outsourcing CO_2 within China. PNAS 2013;110:11654–9.
[11] Laurenzi IJ, Bergerson JA, Motazedi K. Life cycle greenhouse gas emissions and freshwater consumption associated with Bakken tight oil. PNAS 2016;113:7672–80.
[12] Guo RP, Zhu XJ, Chen B, Yue YL. Ecological network analysis of the virtual water network within China's electric power system during 2007–2012. Appl Energy 2016;168:110–21.
[13] Xin L, Feng KS, Siu YL, Hubacek K. Challenges faced when energy meets water: CO_2 and water implications of power generation in inner Mongolia of China. Renew Sust Energy Rev 2015;45:419–30.
[14] Chen SQ, Chen B. Urban energy–water nexus: a network perspective. Appl Energy 2016:905–14.
[15] Duan CC, Chen B. Energy–water nexus of international energy trade of China. Appl Energy 2016;194:725–34.
[16] Wang SG, Chen B. Energy–water nexus of urban agglomeration based on multi-regional input–output tables and ecological network analysis: a case study of the Beijing–Tianjin–Hebei region. Appl Energy 2016;178:773–83.
[17] Feng KS, Hubacek K, Siu YL, Li X. The energy and water nexus in Chinese electricity production: a hybrid life cycle analysis. Renew Sust Energy Rev 2014;39:342–55.
[18] Feng KS, Hubacek K, Sun LX, Liu Z. Consumption-based CO_2 accounting of China's megacities: the case of Beijing, Tianjin, Shanghai and Chongqing. Ecol Indic 2014;47:26–31.
[19] Hubacek K, Feng KS, Minx JC, Pfister S, Zhou NJ. Teleconnecting consumption to environmental impacts at multiple spatial scales. J Ind Ecol 2014;18:7–9.
[20] Lin JT, Pan D, Davis SJ, Zhang Q, He KB, Wang C, et al. China's international trade and air pollution in the United States. PNAS 2014;111:1736–41.
[21] Liu Z, Guan DB, Wei W, Davis SJ, Ciais P, Bai J, et al. Reduced carbon emission estimates from fossil fuel combustion and cement production in China. Nature 2015;524:335–8.
[22] Liu Z, Davis SJ, Feng KS, Hubacek K, Liang S, Anadon LD, et al. Targeted opportunities to address the climate-trade dilemma in China. Nat Clim Change 2016;6:201–6.
[23] Zhao X, Liu JG, Liu QY, Tillotson MR, Guan DB, Hubacek K. Physical and virtual water transfers for regional water stress alleviation in China. PNAS 2015;112:1031–5.
[24] Feng KS, Davis SJ, Sun LX, Hubacek K. Drivers of the US CO_2 emissions 1997–2013. Nat Commun 2015;6:7714.
[25] Davis SJ, Caldeira K. Consumption-based accounting of CO_2 emissions. PNAS 2010;107:5687–92.
[26] Duarte R, Sanchez-Choliz J, Bielsa J. Water use in the Spanish economy: an input–output approach. Ecol Econ 2002;43:71–85.
[27] Sánchez-Chóliz J, Duarte R. Analysing pollution by way of vertically integrated coefficients, with an application to the water sector in Aragon. Cambridge J Econ 2003;27:433–48.
[28] Lopez LA, Arce G, Zafrilla J. Financial crisis, virtual carbon in global value chains, and the importance of linkage effects. The Spain-china case. Environ Sci Technol 2014;48:36–44.
[29] Intended Nationally Determined Contribution (INDC). National Development and Reform Commission of China; 2015.
[30] Energy conservation and emissions reduction comprehensive work plan for the 13th five-year plan (2016–2020) period. Beijing (China): China's State Council; 2016.
[31] Cong R, Lo AY. Emission trading and carbon market performance in Shenzhen, China. Appl Energy 2017;193:414–25.
[32] Miller RE, Blair PD. Input-output analysis: foundations and extensions. Cambridge University Press; 2009.
[33] Input-Output Tables of China 2012. National Bureau of Statistics of the People's Republic of China. China Statistics Press; 2015.
[34] Regional Input-Output Tables of China 2012. National Bureau of Statistics of the People's Republic of China. China Statistics Press; 2016.
[35] Leontief S, Strout A, Barna T. Structural interdependence and economic development. Multi-Regional Input-Output Analysis: St. Martin's Press London; 1963. p. 119–50.
[36] LeSage JP, Pace RK. Spacial econometric modeling of origin-destination flows. J Reg Sci 2008;48:941–67.
[37] Sargento ALM, Ramos PN, Hewings GJD. Interregional trade flow estimation through non-survey models: an empirical assessment. Econ Syst Res 2012;24:173–93.
[38] Zhang W, Wang F, Hubacek K, Liu Y, Wang J, Feng K, et al. Unequal exchange of air pollution and economic benefits embodied in China's exports. Environ Sci Technol 2018:10.1021/acs.est.7b05651.
[39] Zhang YX, Qi SC. 2002–2007 China multi-regional input-output model. Beijing, China: China Statistics Press; 2012.
[40] Zhang YX, Liu Y, Li JF. The methodology and compilation of China multi-regional input-output model. Stat Res 2012;29:3–5.
[41] Emission Inventories by Sectoral Approach. Norwich (UK): China Emission Accounts & Datasets; 2016.
[42] Wiedmann T, Wood R, Minx JC, Lenzen M, Guan D, Harris R. A carbon footprint time series of the UK – results from a multi-region input-output model. Econ Syst Res 2010;22:19–42.
[43] China Economic Census Yearbook. Beijing (China): National Bureau of Statistics of the Peopole's Republic of China; 2015.
[44] China Water Resources Bulletin. Beijing (China): The Ministry of Water Resources of the Peopole's Republic of China; 2013.
[45] Pfister S, Bayer P, Koehler A, Hellweg S. Environmental impacts of water use in global crop production: hotspots and trade-offs with land use. Environ Sci Technol 2011;45:5761–8.
[46] Pfister S, Koehler A, Hellweg S. Assessing the environmental impacts of freshwater consumption in LCA. Environ Sci Technol 2009;43:4098–104.
[47] Cazcarro I, Duarte R, Sanchez Choliz J. Multiregional input-output model for the evaluation of Spanish water flows. Environ Sci Technol 2013;47:12275–83.